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What is the energy balance of grass biomethane in Ireland and other temperate northern European climates?

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ABSTRACT

Biofuels have had bad press in recent years. There are primarily two distinct issues. The biofuel crops with the best yields (such as sugarcane or oil palm) grow in tropical countries where habitat destruction has occurred in association with the biofuel system. First generation indigenous energy crops commonly used for transport fuel in Europe (such as rapeseed and wheat) have low yields and/or the energy balance of the associated biofuel system is poor. This paper shows that grass is a crop with significant yields and grass biomethane (a gaseous renewable transport biofuel) has a very good energy balance and does not involve habitat destruction, land use change, new farming practices or annual tilling. The gross and net energy production per hectare are almost identical to palm oil biodiesel; the net energy of the grass system is at least 50% better than the next best indigenous European biofuel system investigated. Ten percent of Irish grasslands could fuel over 55% of the Irish private car fleet.

Contents

Abbreviations: AD, anaerobic digestion; CH_4, methane; CO_2, carbon dioxide; CSTR, continuously stirred tank reactor; DS, dry solids/dry matter; K, potassium; LCA, life cycle assessment; N, nitrogen; P, phosphorous; PRG, perennial ryegrass; VDS, volatile dry solids.

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1. Introduction

1.1. Background

Biomass, which includes both energy crops and residues, is a renewable energy resource with significant potential in Ireland. It is proposed in this paper to use agricultural grass as a feedstock for anaerobic digestion (AD) in order to generate biomethane for use as a transport fuel. Previous and ongoing work by this research group and others has looked at using grass to generate biogas and biomethane. Work by Murphy and Power [1] outlined the advantages of such as system in Ireland as follows:

- Arable land is not needed for growing grass and direct food substitution is therefore not required.
- Over 90% of Ireland's agricultural land is under grass, yields are high and farmers are familiar with growing the crop.
- Biomethane as a transport fuel is a mature technology.
- Biogas can also be made from wastes and residues, increasing the available feedstock.
- Grassland is currently used for livestock production and a reduction in the size of the national herd is already planned as part of the National Climate Change Strategy.

Research in Belgium looked at the energy and CO_2 balance of grass (and maize) as energy crops for AD [2]. The Cropgen project, which was funded by the EU's 6th Framework Programme, investigated digestion of crops (including grass), focussing on feedstock properties, energy and emissions [3]. A paper was published by Tilman et al. which showed the benefits of grass as a sequester of carbon into the root system [4]. Work by Zhou et al. showed that the energy output of low-input high-diversity grassland biomass on degraded soil is nearly equal to that of ethanol from conventional corn grain on fertile soil in China [5].

1.2. Focus of paper

This paper has an ambition of adding detail to the broad argument for considering grass biomethane as a transport biofuel in a northern European context, as outlined by Murphy and Power [1]. The focus of this paper is a detailed technical analysis of the grass biomethane system. A full energy balance of the system is carried out and compared with the results for other biofuel/energy crop systems. A sensitivity analysis is undertaken to establish the effect of a number of parameters including the use of digestate for fertilizer and the use of wood chips for thermal energy. In essence the paper seeks to establish the gross and net energy production per hectare of a system generating compressed biomethane from grass for use as a transport fuel and to compare this with other biofuel systems.

1.3. Life cycle assessment

A life cycle assessment (LCA) study should systematically and sufficiently address all the environmental aspects of a system. There are a number of different methods by which such a study can be carried out, and it is therefore important that the aim and scope of the study being undertaken are properly defined. The aim of this

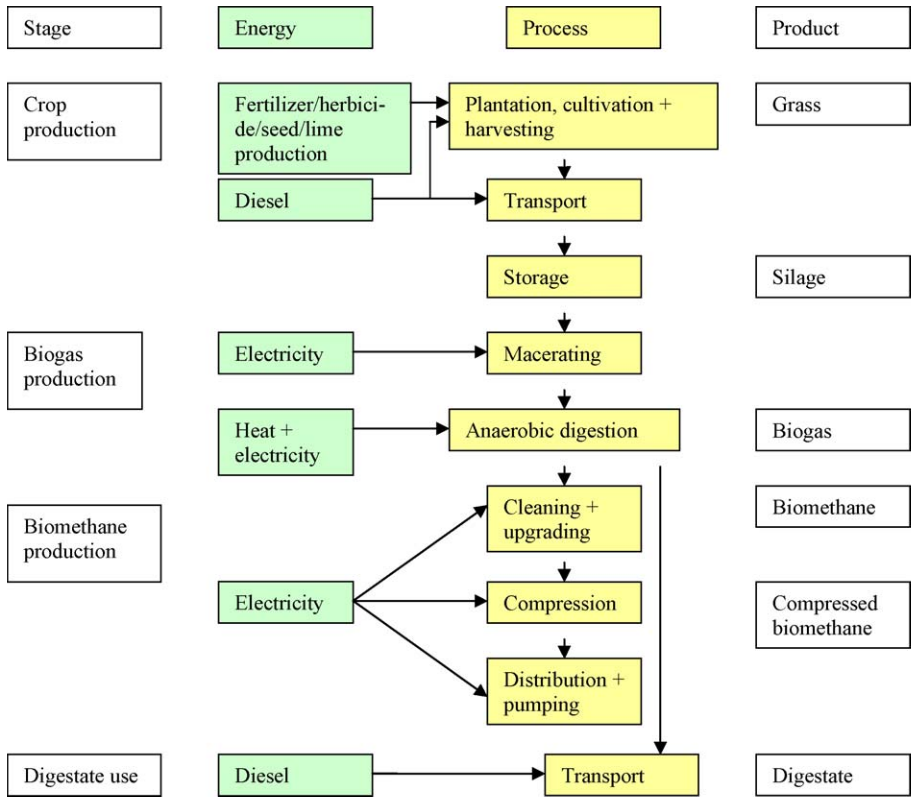

Fig. 1. Life cycle analysis of grass-to-biomethane system.

study is to determine the gross and net energy production of biomethane generated from grass and used as a vehicle fuel in a typical Irish context; the scope of the study may be represented by the cradle-to-grave analogy, the cradle being the production of grass in the field and the grave being the use of the resulting compressed biomethane in the vehicle. The system is represented by the schematic in Fig. 1.

1.4. Direct and indirect energy

The energy used in the process is split into direct and indirect energy. Direct energy is the energy used directly in the production process, e.g. fossil fuel used in machinery. Indirect energy is energy that is used in producing something which is subsequently used in the production process, e.g. fertilizer, herbicides, or diesel. The indirect energy consumed in the manufacture of machinery and equipment is not considered in this study. This is in line with the "Proposal for a Directive on the promotion of energy from renewable sources" from the Commission of the European Communities, which states that the manufacture of machinery and equipment is not taken into account when calculating the greenhouse gas impact of biofuels [6]. The energy required for human labour is also neglected.

2. Agriculture in Ireland

2.1. Importance of grass in Ireland

The most important agricultural crop in Ireland is grass [7]. It is the main feedstock of the livestock industry and is used in beef, dairy and sheep production. An area of 3.9 m ha, or 91% of agricultural land, is used for growing (agricultural) grass in the Republic of Ireland, and this can be split into grass used for pasture, silage, hay, and rough grazing, see Table 1 [8,9]. With animal populations of 5.9 million cattle and 3.5 million sheep in December 2007 [10], the livestock industry is an important contributor to the Irish economy, and exports of beef, sheepmeat and milk products accounted for over €4298 million in the same year [8]. The relative importance of grass is demonstrated by the fact that in 2005 the country had 8% of the total bovine livestock in the EU-27 [11] but, at approximately 4.2 million people [12], less than 1% of the human population [13].

2.2. Grass for energy

2.2.1. Type of grassland

There are three main types of grassland; these are rough-mountain and hill grazing, permanent grassland, and rotational grass. Rough grazing is defined as uncultivated grassland found as unenclosed or relatively large enclosures on hills, uplands, moorland, heaths and downlands [14]. Grass that is grown within an arable rotation is known as rotational or temporary grass. Permanent grassland is grassland in fields or relatively small

Table 1
Agricultural land area and area under grass (from [8,9]).

Area	Area ($\times 10^6$ ha)	% of land area	% of agricultural area
Ireland	6.9	100	–
Total farmed	4.3	62	100
Growing grass	3.9	56	91
Pasture	1.9	28	45
Silage	1.2	18	28
Hay	0.3	4	7
Rough grazing	0.5	7	11
Crop production	0.4	6	9
Cereals	0.3	4	7
Potatoes and sugar beet	0.01	<1	<1
Other crops, fruit and horticulture	0.09	1	2

enclosures that is not in arable rotation, and it is this grassland that is of particular interest for the purpose of growing grass for energy.

2.2.2. Type of grass

Permanent grassland is dominated by perennial grasses and scrub, and contains a wide range of grasses, including productive grasses, clovers and also weeds. Some common species of grass found in permanent grassland are perennial ryegrass (PRG), white clover, timothy, meadow fescue and cocksfoot. Perennial ryegrass dominated pasture is the basis of livestock production in Ireland [7] and PRG makes up around 95% of forage grass seed sales in Ireland [15].

2.2.3. Grass silage

If grass is to be used for energy, it must be harvested and stored, usually as silage. Silage is currently made for feeding livestock; it is the second most important agricultural crop in the country after grass for grazing and is made on 1.24 m ha of grassland and on 86% of Irish farms [16]. With regard to the preferred type of grass for silage-making, it is recommended that in order to achieve high yield and digestibility, reseeded pastures containing medium to late perennial ryegrasses are used [17]. However, despite the benefits of reseeding with PRG, the actual frequency of reseeding permanent pasture is quite low and the proportion of PRG dominant swards is estimated to be only around half (although there is evidence that this is on the increase) [16,18].

2.3. Potential for biogas from agricultural grass

Low family farm incomes and large farming subsidies, especially in the beef and sheep sectors [19,20], mean that there is incentive for farmers to move from livestock farming to alternative enterprises. High self-sufficiency in beef (675%) and sheepmeat (406%) production [8] leave considerable scope for a diversion of grass for energy purposes without affecting domestic food supply. A reduction in the size of the national beef herd, and therefore grassland area used for livestock, is in line with government policy and has already been proposed as part of the National Climate Change Strategy [21–23]. Another factor is Ireland's high energy import dependency, which stands at 91% [24] making us the most import dependent country in the EU. The use of grass biomethane is also in line with the government's White Paper on energy, which has set goals of accelerating the growth of renewable energy sources, promoting energy sustainability in transport and creating jobs, growth and innovation in the energy sector [25].

3. Overview of grass biomethane system

3.1. Basis of analysis

The basis of the analysis is a farm-based grass-to-biomethane facility visited by the authors in Austria in early 2008. The Austrian facility digests the grass from 150 ha, which equates to 1650 tDS/a based on a typical yield of 11 tDS/(ha a). Yields in Ireland tend to be higher and, taking an average value of 12 tDS/ha, the facility modelled under Irish conditions requires a land-take of 137.5 ha/a. This is the equivalent of 5.8 average sized cattle rearing farms with 23.7 ha under grassland [19], assuming that all of the grassland is used for silage.

3.2. Crop production

3.2.1. Reseeding frequency

Reseeding of grassland is recommended in order to improve the grass vigour and growth [26]. LCAs of grass systems in the literature use various reseeding frequencies, from every 2 to 3 years up to every 8 years [2,27–29], and the Irish Farmers Journal recommends reseeding every 4–8 years [26]. However, there is evidence to suggest that increases in yield from reseeded pasture are insignificant when compared to well-managed permanent pasture [30], and in practice reseeding tends to take place less frequently than is recommended. A 2004 survey of 180 farms making silage found that on 54% of farms the pasture was more than 10 years old [18]. The reseeding rate used in this analysis is once every 8 years.

3.2.2. Reseeding method and rate

Direct sowing is the most common method of establishment [14] and the most reliable method of achieving good quality grassland [31]. The existing sward is ploughed in and allowed to rot for a few weeks before sowing. The land is then harrowed, fertilized and rolled before sowing, and harrowed and rolled again after sowing [26]. However, ploughing and cultivating are expensive and for this reason direct drilling, which is a method of seeding without ploughing, has become a popular way of introducing new varieties into an existing sward [32]. The energy required for reseeding can be reduced by 11% if using direct drilling [29]. This analysis assumes that the traditional method of direct sowing is carried out in the autumn. In terms of grass seeding rate, the Irish Farmers Journal recommends 25 kg/ha [26]. UK literature gives rates of between 27 kg/ha and 35 kg/ha, depending on the purpose and duration of the grassland [14,32]. For the purposes of this study, a reseeding rate of 25 kg/ha is used.

3.2.3. Harvesting

Harvesting is assumed to take place twice per year, i.e. two-cut silage; the first cut is usually at the end of May, the second at the beginning of July. Two cuts are the norm in the Irish livestock sector, as a three-cut system is generally deemed uneconomic due to the high costs of harvesting and lower yields from third (or subsequent) cuts. Grass is assumed to be harvested by means of a forage harvester.

3.2.4. Fertilizers

As grassland in Ireland is used primarily as a feed for livestock, the principles currently adopted for fertilization relate to livestock production; the amount of herbage required is determined based on livestock needs, and fertilizer is then applied to promote growth and so reach the required levels. Nitrogen (N), phosphorous (P) and potassium (K) fertilization rates used in this study are taken from Teagasc (The Irish Agriculture, Food and Development Authority) guidelines [33] and are presented in Table 2.

3.2.5. Herbicides

On the majority of Irish pastures weeds are not a problem, but better weed control has the potential to increase output in some cases [30]. Effective weed control is achieved through well planned pasture management [34], which includes drainage, grazing, mowing and fertilizing. In the case of continuous silage, weeds (e.g. dock) may become problematic and herbicide spraying is therefore recommended every 3–4 years [35]. Although a certain percentage of weeds should not have a significant negative effect on biogas yields [36], the presence of weeds may be detrimental to the ensiling process [37]. Herbicide application is assumed once at crop establishment and on two other occasions during the 8-year crop cycle. Application rates are 1440 l/ha of active ingredient at establishment and 2160 l/ha on other occasions [38].

3.2.6. Lime

Irish soil tends to be slightly acidic and it is common practice to apply lime to bring the pH to an acceptable level; the addition of

Table 2
Fertilizer application rates (from [33]).

Establishment year	N (kg/ha)[a,b]		P (kg/ka)[b,c]		K (kg/ha)[b,d]	
	75		70		110	
	1st cut	2nd cut	1st cut	2nd cut	1st cut	2nd cut
First 4 years after establishment	150	125	20	10	200	95
Subsequent years	125	100	20	10	200	95

[a] In the establishment year, half of the N is applied at sowing and half 3–4 weeks later.
[b] Values given assume no slurry application.
[c] P advice assumes as soil P index of 2.
[d] K advice assumes a grass-only crop, i.e. no clover in the sward, a soil K index of 1 and a target yield of 12 tDS/ha.

lime can result in improved availability of nutrients, increased micro-organism and earthworm activity, and an improved response to fertilizer [33]. The optimum pH for grassland in mineral soils is 6.3 [33,39]. Both the frequency of application and the quantity applied per application vary considerably between sites, depending on factors such as soil type and extent of grazing. Teagasc recommends grassland should be limed at least every 5 years [33]. The application of 5 t/ha twice over the 8-year crop cycle is assumed.

3.2.7. Silage yields, properties and suitability for digestion

Silage yields in Ireland are approximately 20% higher than those in other areas of western Europe [40] and are typically between 11 tDS/ha and 15 tDS/ha; yields are generally higher in the southwest of the country and decrease towards the northeast [7,41,42]. A yield of 12 tDS/ha is assumed in this analysis. As is common practice in Ireland, the silage is assumed to be preserved in a pit without the use of additives [16]. The dry matter content of the silage is taken as 220 g/kg, which is typical for pit silage and lower than the corresponding value for baled silage, which is generally around 330 g/kg [16,18,43,44]. The volatile dry solids (VDS) content of grass silage in Cork, Ireland, was found to be 92% on average when expressed as a percentage of dry solids (DS), and the following stoichiometric equation was generated for dry grass: $C_{28.4}H_{44.5}O_{17.7}N$ [45], which suggests that the ratio of carbon to nitrogen (C:N) in grass is 25:1. Work carried out in the UK on the digestion of PRG [28] found the most suitable ryegrass feedstock for AD was cut on a two to four week cycle and had C:N ratios of between 23:1 and 18:1. The most suitable carbon nitrogen ratios for AD are quoted as 15–30:1 [28].

3.3. Biogas production

3.3.1. Anaerobic digestion

Anaerobic digestion, which involves the breakdown of organic material by bacteria in an oxygen free environment, is used to convert biomass to biogas. Anaerobic digestion is a well established process that is reported widely in the literature, although research is still ongoing into optimising the process to increase biogas yields [45].

3.3.2. Reactor type

A continuously stirred tank reactor (CSTR) operating at 10% DS is assumed. Typically the digestion of slurries with a DS content below 12% takes place in a CSTR. The digestion of feedstocks like grass, which have a higher DS content, is achieved through the addition of water and/or recirculated leachate to reduce the DS content to below 12%. It is assumed that the digester operates in the mesophilic temperature range at 38 °C and that the temperature of the incoming feedstock is 10 °C, which is typical for the south of Ireland [46].

3.3.3. Reactor set-up

There are two digestion stages in the process, with two tanks working in series. Approximately 20.5 t of macerated silage is fed into the first tank every day. The total retention time is between about 70 and 80 days, with the substrate spending about half of the time in each tank. The substrate flows by gravity from the first to the second tank, and liquid from the second tank is recirculated back to the first tank to increase the water content. The reason for the long retention time is that the second tank also acts as a storage vessel for digestate, which cannot be land-spread over the winter months. The first tank is always full while the level in the second tank fluctuates.

3.3.4. Loading rate, methane (CH_4) production and mass balance

The loading rate is taken as 1.44 kg VDS/m^3/day, which is within the range quoted in the literature [45] and on site visits to operational plants. Based on this loading rate, the minimum required digester volume is 2847 m^3 (Table 3). A methane yield of 300 m^3 CH_4/kgVDS is assumed from the literature (Table 4) and for a grass loading rate of 20.5 t/day, the gas production in CSTR 1 is calculated as 1775 m^3/day and in CSTR 2 as 444 m^3/day (Fig. 2, Table 3). Total destruction of volatile solids of 55% is assumed [1]. The daily mass balance for the digester is presented in Fig. 2.

3.4. Compressed biomethane production

3.4.1. Upgrading

Biogas from the AD of grass consists of approximately 55% methane (CH_4), 45% carbon dioxide (CO_2) and a small amount of other contaminants. Methane has an energy value of 37.78 MJ/m^3; thus, biogas at 55% CH_4 has an energy value of 21 MJ/m^3. Biomass on a dry and ash-free basis has an energy value of 21 MJ $\pm$ 15%; thus, the destruction of 1 kg of volatile dry solids produces about 1 m^3 of biogas at 55% CH_4 content. Natural or fossil gas consists predominantly of methane (about 97%) and has a higher calorific value in the region of 36–40 MJ/m^3. Biogas must be upgraded or scrubbed to natural gas standard before being used in place of natural gas in vehicles or in the

Table 3
Digester volume and biogas production.

Component	Quantity
Grass yields	12 tDS/ha $\times$ 137.5 ha = 1650 tDS/a
Feedstock	7500 t/a silage @ 22% DS = 20.5 t/day
Annual volatile dry solids	1650 tDS/a @ 90% VDS = 1485 tVDS/a
Volatile dry solids added	4.1 t VDS/day
Loading rate	1.44 kg VDS/(m^3 day)
Minimum required volume	4.1/1.44 = 2847 m^3
Gas production	300 m^3 CH_4/tVDS
CH_4 production	1221 m^3 CH_4/day
Biogas production per day (55% CH_4)	2219 m^3 biogas/day
VDS destruction in CSTR 1	80%
Biogas production in CSTR 1	1775 m^3/day
VDS destruction in CSTR 2	20%
Biogas production in CSTR 2	444 m^3/day

Table 4
Methane content of biogas yields from anaerobic digestion of grass.

CH_4 yield (m^3/tVDS)	Details	Reference
186	Short-term methane yield (30 days) of timothy-clover grass from second harvest	[36]
229	Fresh grass	[28]
230	2 harvests of a permanent crop, all silage used for AD	[2]
299.5	Full scale operational CSTR digesting grass and grass silage, 4 harvests per year	Site visit
302.5[a]	Grass	[47]
300–320	Laboratory scale semi-continuous process	[48]
308[a]	Grass silage	[47]
310–360	Laboratory scale batch process digesting fresh cut meadow foxtail and PRG (respectively)	[48]
320	4 harvests of a permanent crop, first 2 harvests used for animal feed, second 2 harvests used for AD	[2]
342	Ensiled grass	[28]
350	4 harvests of a permanent crop, all silage used for AD	[2]
380	Total methane yield of timothy-clover grass from second harvest	[36]

[a] Calculated from biogas yields given in reference assuming the methane content of biogas is 55%.

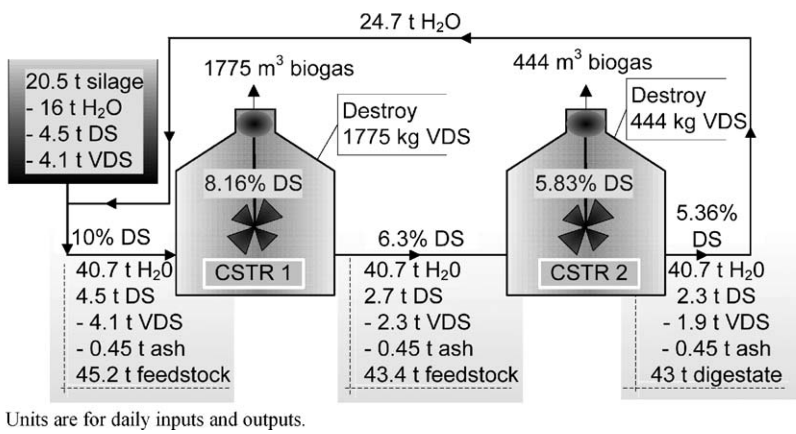

Fig. 2. Daily mass balance of anaerobic digester.

natural gas grid. The calorific value is raised and potentially damaging components, e.g. hydrogen sulphide, are removed.

3.4.2. Compression and filling

Filling stations have to compress the gas from mains pressure (or, in this case, the pressure supplied by the upgrading unit) to about 250 bar in order to fully charge vehicle storage tanks, where natural gas is stored at about 200 bar. There are two types of filling operations used to achieve this, slow-fill and fast-fill. Slow-fill stations have the simpler design, with the dispensing lines connected directly to the compressor, but have longer filling times, typically from 20 min to a number of hours. A fast-fill operation is more complex, but gives typical filling times of only 3–5 min, and is generally used on a traditional service station forecourt. Fast-fill is assumed in this analysis.

4. Technical analysis

4.1. Base case scenario

The assumptions for the base case scenario are listed as follows:

- Crop is grown on an 8-year cycle.
- All fertilizer inputs are met by chemical fertilizers.
- The fuel required to perform agricultural operations is fossil diesel.
- The parasitic electrical demand is imported from a renewable source (wind farm), and the indirect energy associated with electricity production is considered negligible.
- The parasitic heat demand of the digester is met by burning biogas produced on site.
- All digestate is transported for use off-site.
- Heat losses of 15% occur in the digester.
- Losses of 1.5% occur in the upgrading system.

4.2. Gross energy

A range of values was found in the literature for the quantity of methane produced per tonne of grass/grass silage, from 186 m^3/tVDS to 380 m^3/tVDS (Table 4). Yields vary depending on a number of factors, such as whether silage or fresh grass is used, the retention time, the digester type, and the maturity of the grass at harvesting [2,28,36,47,48]. This analysis assumes a two-cut silage system with CH_4 yields of 300 m^3/tVDS (Fig. 2). The methane content of biogas from grass silage is 55% [1]; thus the gross energy production from grass is calculated as 122.4 GJ/ha (Table 5).

4.3. Parasitic energy in crop production

4.3.1. Overview

The parasitic energy used in agriculture includes the direct energy used in planting, cultivating and harvesting the crop, as well as the indirect energy used in the manufacture of fertilizers and other inputs. A range of energy values is reported in the literature for each operation, and values differ depending on variables such as the soil type, ground conditions and the exact equipment used. The indirect energy is crucially dependent on the production conditions, i.e. the specific machinery and processes used. The values used in this analysis are in so far as possible based on the Irish/UK context. The total energy use in agriculture is 20.6 GJ/(ha a) (Tables 6 and 7), with indirect energy use responsible for over 85% of this.

Table 5
Gross energy per hectare.

Component	Quantity
Annual volatile dry solids	1485 tVDS/a
Methane production	300 m^3/tVDS
Annual methane	445,500 m^3 CH_4/a
Energy content of methane	37.78 MJ/m^3
Annual biogas[a]	810,000 m^3/a biogas
Annual energy	16.8 TJ/a
Area under grass	137.5 ha
Gross energy per hectare	122.4 GJ/(ha a)

[a] CH_4 content of biogas is 55% [1].

4.3.2. Direct energy

The operations and inputs required for planting, cultivating and harvesting the sward are discussed in Section 3.2. Yields of fresh silage are about 65 t/ha and the silage is assumed to be transported an average distance of 5 km to the silage pit (grass is 18% DS when cut, 22% DS in the silage pit). The 5 km transport distance is considered to be relatively conservative; if the AD plant is located in the centre of a circle of area 137.5 ha (the total area harvested for grass silage), the radius of the circle is 0.662 km. The total direct energy used in agriculture is calculated as 2.91 GJ/(ha a) (from [2,27–29,49–52], Table 6) and is similar to the value of 2.92 GJ/ha reported for total annual fuel use on Irish farms (forage operations) [53]. By far the largest contributor to the direct energy used in silage production, at approximately 60% of the total, is the energy required for forage harvesting.

4.3.3. Indirect energy

The indirect energy is calculated as 17.7 GJ/(ha a) (from [2,27,29,50–52,54,55], Table 7), the largest component of which is the production of nitrogen fertilizer, which is responsible for 72% of indirect energy in agriculture. It is also significant in the overall energy balance, accounting for 63% of the total energy used in agriculture.

4.4. Parasitic energy in biogas production

4.4.1. Parasitic heat demand of digester

In the base case scenario biogas is used to satisfy thermal parasitic demand. The thermal energy requirement for AD is calculated as 17.1 GJ/(ha a) (Table 8). The temperature of the feedstock needs to be raised 28 °C in the digester. As the feedstock has a low solids content (10%), its specific heat is assumed to be similar to that of water. Heat losses from the digester as found in the literature vary from 20% [2] to around 40% [56] of the energy required for substrate heating. With good insulation, and taking the climatic conditions in Ireland into consideration, a value of 15% is readily available. This analysis may be considered conservative as the recycled leachate will be warmer than 10 °C. The energy required to heat the digester does not account for the contribution from metabolic heat generation, also called the self-heating effect. The amount of heat provided by metabolic generation is uncertain [3] and therefore neglected, giving a more conservative result. Biogas losses in the anaerobic digester are assumed to be minimal and to be accounted for in the yield value used (300 m^3/tVDS).

4.4.2. Macerating, mixing and pumping

From an analysis of an existing facility, the energy required to chop the grass silage is 2 kWh/t of silage added. The electrical demand for mixing slurry digesters operating at about 12% DS is 10 kWh/t of slurry digested [57]. The total annual feedstock is 16,500 t/a (silage plus water). Pumping is required to recirculate 9000 t/a of liquid from the second to the first tank; the energy for

Table 6
Direct energy in agriculture.

Operation	Number of operations[a]	Energy per operation (MJ/ha)	Average energy (MJ/(ha a))	Literature reviewed[c]
Ploughing	1	800	100	[2,27–29,50,51]
Sowing	1	160	20	[2,27–29,51]
Harrowing	2	169	42	[2,27–29,51]
Rolling	2	56	14	[27,28,50,51]
Fertilizer application	18	72	162	[2,27–29,51,52]
Lime application	2	90	23	[27]
Herbicide application	3	48	18	[2,27,29,51,52]
Forage harvesting	16	877	1754	[2,28,29,50]
Silage transport[b]	16	179	358	[49]
Ensiling	16	208	416	[2,29]
Total			2906	

[a] The number of operations is over the 8-year crop cycle.
[b] The energy used in transport is 1.1 MJ/(t km) × 65 t/ha of fresh silage × 5 km for two harvests.
[c] Literature reviewed for "Energy per operation" data.

Table 7
Indirect energy in agriculture.

Manufacture of:	Total application (kg/ha)[a]	Energy for production (MJ/kg)	Total energy (GJ/(ha a))	Literature reviewed[b]
Fertilizer				
Nitrogen (N)	2,075	50	12.97	[2,27,50–52,54,55]
Phosphorous (P)	310	8.6	0.33	[2,27,29,50,51,54,55]
Potassium (K)	2,470	6.7	2.07	[2,27,29,50,51,54,55]
Herbicide	5.76	264	0.19	[27,29,50–52]
Seed	25	12	0.04	[27,52]
Lime	12,000	1.2	1.8	[27,50,54,55]
Fuel		10% direct fuel use	0.29	[29]
Total			17.69	

[a] The total application is over the 8-year crop cycle.
[b] Literature reviewed for "Energy in production" data.

Table 8
Parasitic heat demand of digester.

Component	Quantity
Specific heat capacity of water	4.184 MJ/(t °C)
Total water content of feedstock	14,850 t/a
Thermal demand of feedstock	62 GJ/°C
Assume temperature rise	28 °C
Thermal demand	1,740 GJ/a
Assume boiler efficiency	85%
Primary thermal demand	2,047 GJ/a
Quantity of land under grass	137.5 ha
Parasitic demand of digester	14.9 GJ/(ha a)
Heat loss (15%)	2.2 GJ/(ha a)
Total heat demand	17.1 GJ/(ha a)

Table 9
Energy in biogas production.

Operation	Calculation	Annual energy (GJ/(ha a))	% total
Macerating[a]	2 kWh/t × 7500 t/a	0.39	1.8
Mixing[b]	10 kWh/t × 16,500 t/a	4.32	19.6
Heating + heat losses	Table 8	17.12	77.8
Biogas losses	Accounted for in yield value	0	0
Pumping[c]	2.5 MJ/t × 9000 t/a	0.16	0.7
Indirect	Renewable sources assumed	0	0
Total		21.99	100

[a] Macerated silage: 1650 tDS/a @ 22% DS = 7500 t/a silage; energy demand from analysis of an existing facility.
[b] Mixed substrate: substrate is 10% DS; total substrate = 1650 tDS/a × 10 = 16,500 t/a; energy demand from [57].
[c] Pumped liquid: 16,500–7500 = 9000 t/a; energy demand from [49].

pumping is assumed to be the same as for loading liquid phase digestate, which is taken as 2.5 MJ/t [49]. It is assumed that the macerator, pump and mixer run on electricity. The total parasitic energy in biogas production is calculated as 22 GJ/(ha a) (Table 9).

4.5. Parasitic energy in biomethane production

4.5.1. Scrubbing and compression

The amount of electricity needed for biogas scrubbing depends on the technique used, but is generally within the range of 0.3–0.6 kWh/m^3 of upgraded biomethane [58–60]. The electricity required for compression falls within a similar range (0.35 kWh/m^3 [59,60] to 0.6257 kWh/m^3 [61]). A value of 0.35 kWh/m^3 is assumed for both operations, which equates to 7.13 GJ/(ha a) in total (Table 10).

Table 10
Energy in biomethane production.

Operation	Unit energy[a]	Biomethane treated[b]	Annual energy (GJ/(ha a))	% total
Scrubbing	0.35 kWh/m^3 biomethane	389,125 m^3/a	3.57	50
Compression	0.35 kWh/m^3 biomethane	389,125 m^3/a	3.57	50
Distribution	Assumed negligible	–	0	0
Indirect	Renewable electricity assumed	–	0	0
Total			7.13	100

[a] From [58–61].
[b] See Table 12.

Table 11
Energy in digestate loading and transport.

Operation	Calculation[a]	Annual energy (MJ/(ha a))	% total
Loading	2.74 MJ/t × 15,695 t/a	0.31	13.4
Transport	1.6 MJ/(t km) × 10 km × 15,695 t/a	1.83	0.8
Indirect	10% of fuel use	0.18	7.8
Total		2.32	100

[a] Energy demand from [29,49,56].

4.5.2. Methane losses in upgrading

The amount of losses in an upgrading system depends on the technology used. A study in Sweden [58] reported losses of approximately 10% in operational upgrading plants, even though losses of only 1–2% were quoted in the design specification. Work undertaken by Murphy and Power [59] used a value of 1.5%. Some upgrading plants with higher losses operate a system whereby the off-gas is reused (e.g. in a low-calorific burner or added to the raw biogas), effectively resulting in negligible losses. For this analysis, losses of 1.5% are assumed, which is the equivalent of 10,451 m^3 of biogas per year.

4.5.3. Distribution

It is assumed that the filling station is located either on the same site as the AD and upgrading facility or nearby on the same local distribution network. Work for the European Commission [61] reports that the energy required for natural gas local distribution is zero. This is because the high pressure trunk lines that feed low pressure networks provide sufficient pressure energy to supply local distribution. The total parasitic energy in biomethane production is calculated as 7.13 GJ/(ha a) (Table 10).

4.6. Parasitic energy in digestate loading and transport

It is assumed that the second tank is emptied completely when the digestate is removed. The energy required for loading is 2.5 MJ/t and 7 MJ/t for liquid and solid digestate respectively [49]. Assuming that the digestate is not separated (i.e. 5.36% DS, see Fig. 2), the energy needed for loading is 2.74 MJ/t. It is assumed that the digestate is transported 10 km for use off-site. The energy required for transport by truck is 1.6 MJ/(t km) including empty return [56]. Digestate production is 43 t/day (Fig. 2) or 15,695 t/a. Indirect energy is 10% of fuel use [29]. The total parasitic energy in digestate loading and transport is therefore 2.3 GJ/(ha a) (Table 11).

Table 12
Gross biomethane production—base case.

Component	Quantity	Gas volume
Gross energy per hectare	122.4 GJ/(ha a)	810,000 m^3/a biogas
Parasitic demand + heat loss	17.1 GJ/(ha a)	113,274 m^3/a biogas
Biogas available for upgrading	105.3 GJ/(ha a)	696,726 m^3/a biogas
Losses in upgrading (1.5%)	1.6 GJ/(ha a)	10,451 m^3/a biogas
Gross biomethane production[a] (energy available at the pumps)	103.7 GJ/(ha a)	389,125 m^3/a biomethane
Energy consumption of car[b]	39 GJ/a	–
1 ha fuels	2.7 cars/a	–
137.5 ha fuels	365.6 cars/a	–

[a] The methane content of biomethane is assumed to be 97%. This is in line with the target of ≥97% CH_4 used in operational plants (that inject biomethane into the natural gas grid) visited by the authors in Austria.
[b] The average specific fuel consumption of new cars on the road in Ireland in 2006 was 2.3 MJ/km and the combined average mileage for petrol and diesel cars was 16,985 km/a [62], giving an average annual vehicle consumption of approximately 39 GJ/a.

Table 13
Energy balance of grass to biomethane system.

Energy	Base case		Scenario 1		Scenario 2	
	GJ/(ha a)	% gross energy	GJ/(ha a)	% gross energy	GJ/(ha a)	% gross energy
Gross energy production	122.41	100	122.41	100	122.41	100
Parasitic energy demands						
Agriculture direct	2.91	2.4	8.59	7	2.91	2.4
Agriculture indirect	17.69	14.5	4.14	3.4	17.69	14.5
Biogas production direct	21.99	18	21.99	18	21.99	18
Biogas production indirect	0	0	0	0	0.34	0.3
Biomethane prod direct	7.13	5.8	7.13	5.8	8.23	6.8
Biomethane prod indirect	0	0	0	0	0	1
Upgrading losses	1.58	1.3	1.58	1.3	1.87	1.5
Digestate transport direct	2.14	1.7	1.23	1	2.14	1.7
Digestate trans indirect	0.18	0.1	0.09	0.1	0.18	0.1
Total parasitic energy demand	53.62	43.8	44.74	36.6	55.38	45.2
Net energy	68.79	56.2	77.66	63.40	67.03	54.8

Table 14
Nutrient content of digestate and chemical fertilizer requirement.

Details	Units	N	P	K
Annualised fertilizer requirement[a]	kg/(ha a)	259	39	309
Annual digestate production	t/(ha a)		114 (NPK)	
Nutrient content of digestate (available)[b]	kg/t	2.1	0.087	3.08
Annual nutrient content of digestate	kg/(ha a)	239	10	351
Annualised chemical nutrient requirement	kg/(ha a)	20	29	0

[a] Fertilizer requirements are averaged over the 8-year crop cycle.
[b] The digestate is assumed to be 5.36% DS (Fig. 2). There is limited information in the literature regarding the nutrient content of grass digestate. The value used here is from an analysis by Holliday et al. [28], which is based on liquid grass digestate from a CSTR at 3.5% DS. This gives a conservative value for the nutrient content of digestate used in this analysis.

4.7. Summary of energy balance

4.7.1. Gross biogas and biomethane production

The gross energy of the system is 810,000 m^3/a of biogas or 122.4 GJ/(ha a) (Table 12). The gross biomethane production is the quantity of energy in the form of biomethane available for sale at the pumps. It is calculated from the gross biogas produced minus the biogas used to meet the parasitic heat demand and any losses in the system. The gross biomethane production is 103.7 GJ/(ha a), which is sufficient to fuel 2.7 cars per hectare (from [62], Table 12). This modelled 137.5 ha farm can power 365 cars.

4.7.2. Net energy

The net energy of the grass to biomethane system is 69 GJ/(ha a) (Table 13). The most significant components of the parasitic energy demand are the indirect energy required in agriculture and the direct energy required in biogas production, at 33% and 42% of the total parasitic demand respectively. Nitrogen fertilizers are the largest energy user in agriculture, and biogas heating the most significant demand in biogas production. As these are the two most significant parasitic energy demands, it is these parameters that are varied in the sensitivity analysis.

4.8. Scenario 1—fertilizers

4.8.1. Revised energy balance

All of the digestate is used as fertilizer, resulting in a reduced requirement for chemical fertilizer (Table 14). The changes in the energy balance are summarised as follows:

- A reduced quantity of chemical fertilizer leading to reduced indirect energy requirements for the manufacture of fertilizer.
- A reduction in the number of chemical fertilizer applications (assume chemical fertilizers are applied twice in the establishment year and once per year in following years).
- Inclusion of energy required for digestate application of 16.6 MJ/t (based on energy requirements for spreading liquid and solid digestate of 17 MJ/t and 14 MJ/t respectively [49], and a digestate solids content of 5.36%).
- A reduction in the digestate transport distance to 5 km (assumed to be the same as silage transport distance).

By reusing the digestate as fertilizer, the net energy of the system is increased by almost 10 GJ/(ha a) compared with the base case scenario, from 69 GJ/(ha a) to 78 GJ/(ha a) (Table 13).

4.8.2. Clover

The addition of clover (a herbage legume) in the sward can further reduce the requirement for nitrogen fertilizer. The root nodules of herbage legumes contain rhizoidal bacteria that fix nitrate in the soil. White clover can supply up to the equivalent of 120–150 kg/ha of fertilizer N [63], which, if used in conjunction with digestate, could negate the need for chemical nitrogen.

Table 15
Gross biomethane production—scenario 2 (wood chips used for parasitic heat demand).

Component	Quantity	Biogas
Gross energy per hectare	122.4 GJ/(ha a)	810,000 m^3/a biogas
Parasitic demand + heat loss	17.1 GJ/(ha a)	0 m^3/a biogas
Biogas available for upgrading	122.4 GJ/(ha a)	810,000 m^3/a biogas
Losses in upgrading (1.5%)	1.8 GJ/(ha a)	12,150 m^3/a biogas
Gross biomethane production[a] (energy available at the pumps)	120.6 GJ/(ha a)	452,389 m^3/a biomethane
Energy consumption of car[b]	39 GJ/a	–
1 ha fuels	3.1 cars/a	–
137.5 ha fuels	425.1 cars/a	–

[a] The methane content of biomethane is assumed to be 97%. This is in line with the target of ≥97% CH_4 used in operational plants (that inject biomethane into the natural gas grid) visited by the authors in Austria.
[b] Average annual vehicle consumption is 39 GJ/a (Table 12).

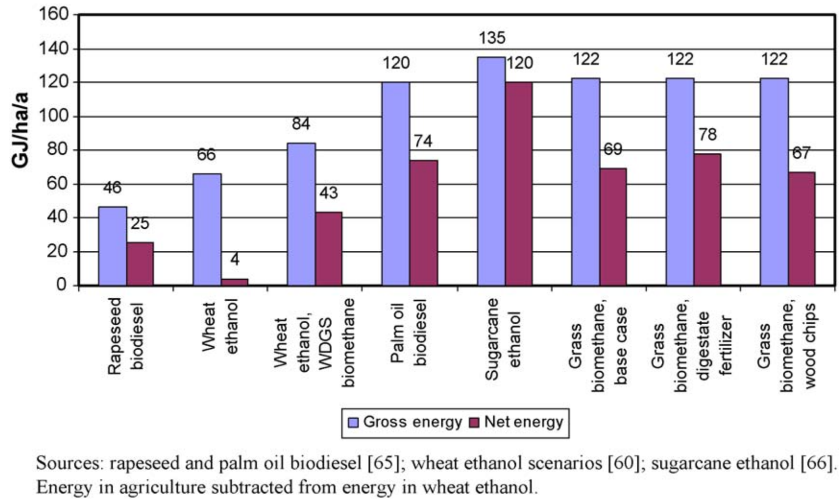

Fig. 3. Comparison of gross and net energy output of selected energy crop biofuel systems.

However, pastures containing clover require different management practices than standard pastures and an analysis of the use of clover is outside the scope of this study.

4.9. Scenario 2—wood chips for thermal demand

In a number of operational biogas plants visited by the authors, the parasitic thermal demand of the digester is not met by burning biogas. The produced biomethane has an enhanced asset value due to the carbon credit associated with the biofuel. It is therefore considered more economically viable to sell the biogas/biomethane and to meet the thermal demand by burning a cheaper fuel, such as oil or wood chips. In this analysis it is assumed that the parasitic heat demand of the digester is met by burning wood chips, and all the biogas is upgraded to biomethane. The parasitic demand of the system is slightly higher than in the base case (Table 13), as the energy used in the production and transport of wood chips has to be taken into account (0.02 MJ of primary energy per 1 MJ of biomass stored [64], which equates to 342 MJ/(ha a)). The volume of biogas sent for upgrading is increased, and 452,389 m^3/a is now available for sale at the pumps. This could fuel 425 cars (Table 15), compared with 366 in the base case scenario.

5. Conclusions

5.1. Comparison of energy production

A big issue for Europe and northern America is the inability to produce indigenous biofuel crops with the yield per hectare found in tropical countries. In particular, it is very difficult to match the yields of sugarcane (Brazil) and palm oil (South East Asia). However, the gross energy from the grass biomethane system compares favourably with the tropical systems ([65,66], Fig. 3). Only the sugarcane-to-ethanol system has higher gross energy (135 compared to 122 GJ/(ha a)). Grass biomethane has a similar gross energy to palm oil biodiesel. Of interest here is the fact that grass biomethane is far superior to traditional first generation European indigenous biofuel systems [60,65]. It has a considerably higher gross energy than rapeseed biodiesel and wheat ethanol systems. It also has a considerably higher gross energy than the improved wheat ethanol system that allows for straw for thermal energy and biomethane production from wet distillers grain and solubles (WDGS). The net energy of the grass to biomethane system also compares well with the other energy crops (Fig. 3). With regard to the base case scenario, the net energy is similar to the palm oil biodiesel system, and significantly higher than the rapeseed biodiesel and wheat ethanol systems. The net energy for scenario 2 (wood chips) is similar to the base case, while scenario 1 (digestate fertiliser) has the best net energy after sugarcane ethanol. Sugarcane ethanol has a significantly higher net energy than all of the other systems, at 120 GJ/(ha a) compared to the next best system at 78 GJ/(ha a) (scenario 2), but cannot be grown in northern Europe.

5.2. Advantages of grass biomethane

The grass biomethane system has a number of distinct advantages over other systems. Firstly, grass biomethane can be produced in Ireland without the need for land use change, whereas palm oil biodiesel or sugarcane ethanol must be imported from countries such as Thailand or Brazil, where there is concern over deforestation, carbon emissions and ecological damage resulting from the conversion of land for energy crop production. In addition, indigenous energy crops bring with them the added advantages of local employment and local economic benefit. When compared with the other Irish based systems (rapeseed and wheat), grass based biomethane is preferable as it does not require arable land to grow. Only 9% of Irish agricultural land is arable (compared to 91% under grass), so a diversion of arable land away from food production would have a significant impact. Coupled with this is the fact that grassland does not need to be ploughed and planted each year, unlike rapeseed and wheat which require annual ploughing.

5.3. Available energy

There are 3.4 million hectares of grassland potentially available for energy production in Ireland (silage, hay and pasture). If 10% of this land was made available for energy, over 1.05 million cars could be fuelled with compressed biomethane. There were 1.88 million private cars in Ireland in 2007 [67]; thus 10% of grassland could fuel over 55% of passenger cars.

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